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Crashworthiness of Civil Aircraft subject to Soft Soil and Concrete Impact surface

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Abstract

The impact response of civil aircraft subject to different soft soil and concrete ground is investigated. Typical finite element model of fuselage section is built based on sound simplification. Several different soft soil and concrete impact surfaces are adopted here. The drop test of civil aircraft is conducted subject to 7m/s impact velocity. The impact response of ground and civil aircraft are revealed. Result shows that ground material has great influence on the crashworthiness of civil aircraft. Soft soil ground could dissipate a part of impact kinetic energy, and failure element of concrete ground would be deleted. Ground with larger stiffness would absorb less internal energy and undergo smaller deformation. The relevant civil aircraft would also have larger plastic deformation, and greater initial peak acceleration would be suffered by occupant.

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Keywords: Crashworthiness, Civil aircraft, Finite element method, Soft soil, Concrete

1. Introduction

Crashworthiness is one of the most important aircraft design factors which is related with the safety of occupant during impact accident. Although great development of aerospace technology is

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exhibited, much more attention has been focused for the crash risk is not zero. To arrive at the designated objective, some crashworthiness terms in China Civil Aviation Regulations (CCAR) Part 25 are established.

Crashworthiness is a very complex problem for the nonlinear transient nonlinear process. Dissipating impact kinetic energy is one of the most important factors, and fuselage could determine the entire impact characteristics. To investigate and improve the crashworthiness of civil aircraft, many kinds of researches are conducted for Boeing B737 et al[1-2]. Rigid floor is the most common and dangerous situation for impact event, but water, soft soil and concrete may be also the impact surface[3-6]. The impact characteristics of civil aircraft with soft soil and concrete demonstrate different response with that of rigid floor, and the dynamic response of soft soil and concrete has great influence on the crashworthiness of civil aircraft. However, till now, few studies about the crashworthiness of civil aircraft with different soft soil and concrete ground condition are reported.

The impact response of typical civil aircraft with soft soil and concrete are investigated here. Due to the inefficiency of experiment test, explicit finite element method is adopted to simulate the drop test of civil aircraft. Different soft soil and concrete material are chosen as the impact surface. Impact response of civil aircraft and ground are exhibited. The result of this paper gives some guidance to the aircraft designer for crashworthiness consideration.

2. Description of impact problem and research method

2.1. Impact problem of civil aircraft

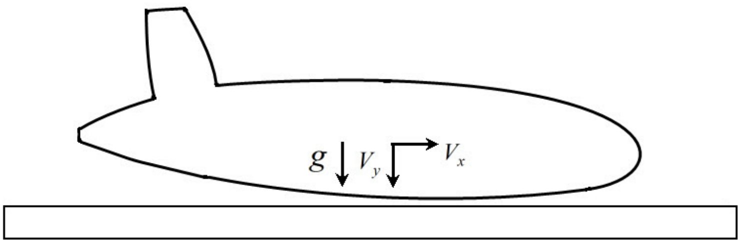

Fig. 1 The impact of civil aircraft with ground

The civil aircraft collides with ground with horizontal velocity V_x and vertical velocity V_y subject to gravitational acceleration. Aerodynamic force is ignored for its small influence. The impact process of civil aircraft obeys the fundamental dynamic equations. Vertical velocity leads to plastic deformation, while horizontal velocity is reduced to zero by friction force. Here, vertical drop test subject to 7m/s is simulated, and the crashworthiness of civil aircraft with soft soil and concrete ground condition is compared.

2.2. Research method

The impact problem of civil aircraft is very complicated, and some necessary steps are required to keep the accuracy and efficiency. The following research flow exhibited as Figure 2 is adopted. First of all, simplified fuselage section is given based on some reasonable simplification principles. Just the substructure under the cabin floor is considered. Then, geometrical model is built in CATIA, doublers and fasteners are neglected. The next step is to import the geometrical model to PATRAN software, and finite element model could be established. Finally, drop test of civil aircraft is conducted with MSC/DYTRAN and LS-DYNA, and numerical simulation result is given by analyzing data.

The civil aircraft geometrical model is shown as Figure 3, and it consists of frame, cabin floor, stringers and strut. Some simplifications are assumed to keep the model as simple as possible as following.

- Just fuselage section with three frames is considered here because it could reveal the impact characteristics of entire civil aircraft structure.
- The structure above cabin floor, seat and occupant are modeled as rigid block for the deformation could be neglected.
- Connecting pieces, doublers and joints are ignored because just overall deformation is concerned.

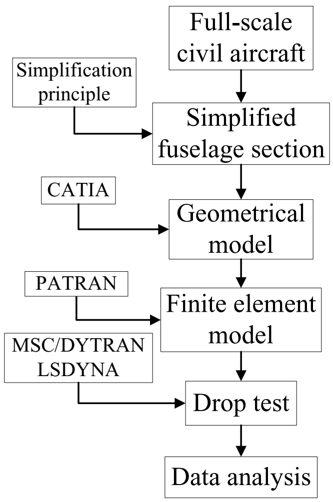

Fig. 2 Research flow of civil aircraft impact problem

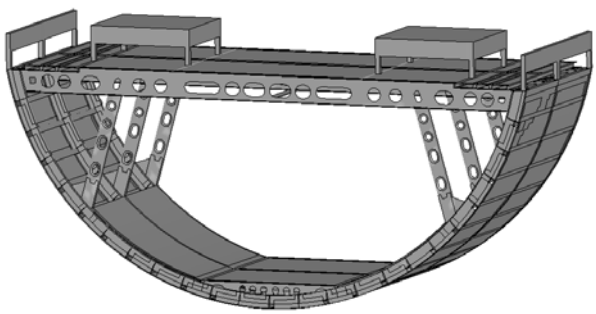

Fig. 3 Geometrical fuselage section

3. Finite element Model

3.1. Civil aircraft

Civil aircraft finite element model is built based on the above geometrical model. The structure above cabin floor, seat and occupant are simulated with solid elements, and their material is rigid.

Beam element is used to model stringers and cabin-floor beam, and other parts are shell element. The thickness of shell element are adjusted to maintain the consistency of model with physical structure considering that joints, fasteners, doublers and other connection pieces are ignored. Some key parameters such as total mass, inertia moment and center of mass are checked. The finite element model of frame, strut, skin and stringers are shown as Fig 4. Nearly all of shell elements are quadrangular, and triangular shell is avoided to employ because it is too stiff. Finally, finite element model consists of 34118 nodes and 32167 elements. Al-2024 and Al-7075 are the two kinds of metal materials of civil aircraft.

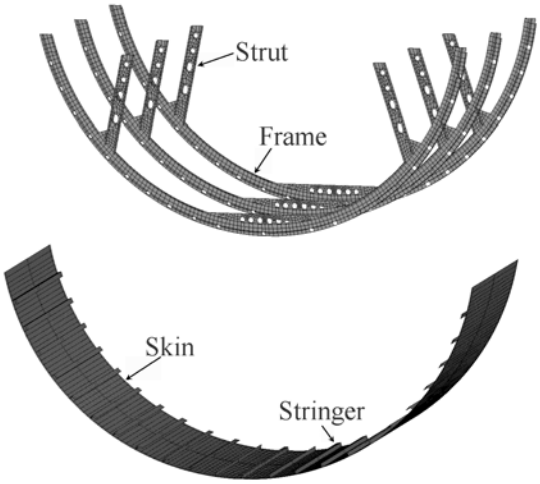

Fig. 4. (a) Finite element of frame and strut; (b) Finite element of skin and stringer

3.2. Soft soil model

Soft soil is a two-phase material consisting of mineral and air/water, and it is difficult model soft soil mechanical characteristics in terms of general stress-strain relationship. To get the proper physical phenomenon of soft soil, several numerical models have been used in commercial finite element software. Soil and crushable foam in LS-DYNA provides a simple model for soft soil and works like fluid behavior. The deviatoric behavior is governed by a pressure-dependent flow rules as Eq. (1).

$$\phi_s = 1/2\, s_{ij}s_{ij} - (a_0 + a_1 p + a_2 p^2) \tag{1}$$

Where a_0, a_1 and a_2 are material constant, s_{ij} and p is the deviatoric stress and pressure.

Eq. (2) is satisfied if on the yield surface.

$$\phi_s = 0 \tag{2}$$

To eliminate the pressure dependence of yield strength, the following conditions should be met.

$$a_1 = a_2 = 0;\ a_0 = 1/2\, s_{ij}s_{ij}$$

The pressure versus volumetric strain curve is imported to determine volumetric yielding behavior. Volumetric strain is given by the nature logarithm of the relative volume for the ratio between the current volume and initial volume, and it is negative in compression. Unloading behavior like elastic from the designated curve is assumed to tensile cutoff instead of zero.

Several different sand materials are adopted here to investigate the civil aircraft crashworthiness performance such as unwashed sand (UWS), low density dry sand (LDD), high density in situ moisture sand (HDI), high density flooded sand (HDF) and high-grade washed sand (HWS) provided by NASA[7-8]. The soft soil material characteristics are listed as Table 1.

Table 1. Sand material

Soft soil material	Density (Kg/mm^3)	Shear modulus (GPa)	Bulk unloading modulus (GPa)	A0 (GPa^2)	A1 (GPa)	A2 --	Pressure cutoff (GPa)
UWS	2.05E-5	2.30E-2	1.34E-1	3.0E-4	2.56E-6	0.543	-6.89E-6
LDD	1.26E-5	1.39E-3	2.23E-1	0	0	0.504	0
HDI	1.57E-5	3.25E-3	1.11E-1	6.5E-5	1.29E-5	0.637	0
HDF	1.41E-5	3.62E-3	1.31E-1	9.7E-7	2.56E-5	0.518	0
HWS	1.42E-5	1.84E-3	6.89E-2	0	0	0.3	0

3.3. Concrete model

Concrete regarded as heterogeneous material is a kind of mixed materials with cement, aggregate and water, etc. It is impossible to simulate concrete material behavior with just several models for the complicated cement material, variational aggregate and admixture. However, there are some available concrete models in LS-DYNA software. Two kind of concrete models are adopted here, i.e. concrete with damage and CSCM concrete[9]. The concrete with damage model could simulate buried steel reinforced concrete structure. CSCM concrete is a smooth or continuous surface cap model with interaction between the shear yield surface and hardening cap. Initial damage surface keep consistency with yield surface, and viscoplasticity is used to model rate effects.

4. Soft soil and concrete impact test data

4.1. Impact response of ground

Ground may absorb a part of impact kinetic energy, and it functions as shock absorber. Thus, different grounds exhibit distinct different crashworthiness performance. Different from rigid ground, soft soil and concrete may suffer large deformation, and the impact kinetic energy may be stored as the internal energy. The deformation of ground is obtained with finite element method. The distortion of mesh is a little large enduring impulsive load. Typical ground deformation with LDD and HDI sand ground are shown as Figure 5 and 6. It is demonstrated that LDD sand has larger deformation than that of HDI sand. Concrete material is stiffer than that of soft soil, and there is almost no elastic deformation. In addition, material failure is important for the simulation of impact process, but it is hard to give true failure criterion. The final concrete ground with failure criterion is exhibited as Figure 7. Element would be deleted once the failure criterion is satisfied. Thus, a hole appears on the ground after the impact event. Just very small deformation of ground is exhibited if no failure is involved.

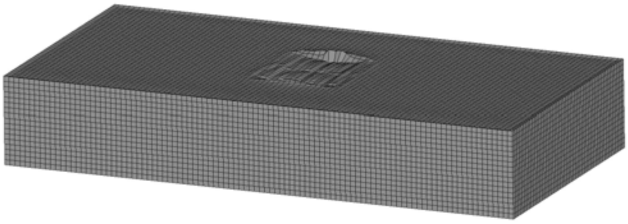

Fig. 5 LDD sand deformation under impact

Ground could affect the impact response of civil aircraft because some parts of impact kinetic energy are transferred to its internal energy. Consequently, the internal energy of ground is an important parameter to measure its influence. The internal energy history curves of different sand material are shown as Figure 8. HWS has the strongest energy absorption ability, and its internal energy would increase over time. It seems that there is no rebound during impact event. Other four soft soil materials demonstrate more or less elastic rebound, and the internal energy from high to low is LDD, HDI, HDF and UWS. The result of internal energy is corresponding with that of ground deformation. In addition, the energy absorption of concrete is relatively small.

It is concluded that the ground material types have great influence on the deformation and energy absorption of ground. HWS ground has the strongest energy absorption ability, and that of UWS is the least.

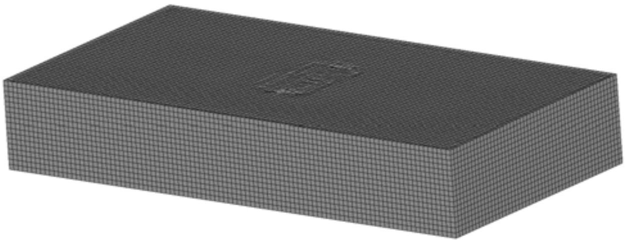

Fig. 6 HDI sand deformation under impact

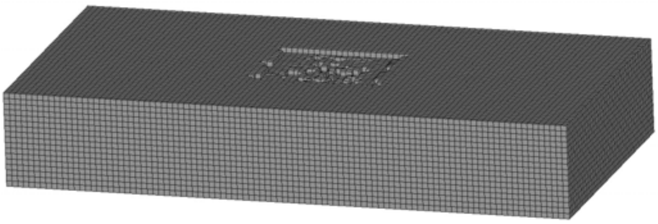

Fig. 7 Concrete ground deformation during impact process

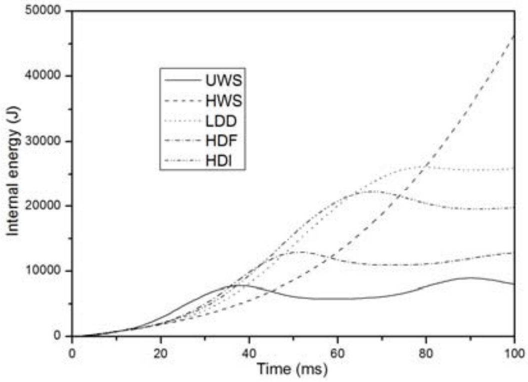

Fig. 8 Internal energy of different soft soil material

4.2. Impact response of civil aircraft

Impact process of civil aircraft consists of final failure behavior, initial impact, energy absorption and acceleration history, etc. Three typical failure models are exhibited as Figure 9-11 subject to LDD, HDI and concrete impact surface respectively. Civil aircraft has small deformation subject to LDD sand shown as Figure 9. Just two plastic hinges on their both sides, and bottom impact area has no obvious plastic deformation. HDI sand is stiffer than LDD, thus a bottom plastic hinge appears during impact process shown as Figure 10. In addition, the failure model of civil aircraft is asymmetry for HDI sand. Finally, the failure behavior for concrete is exhibited as Figure 11. Larger deformation than that of former is demonstrated because concrete impact ground has greater stiffness.

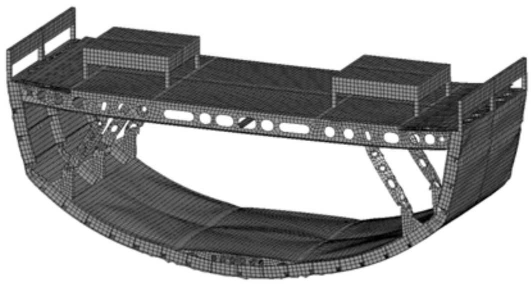

Fig. 9 Civil aircraft deformation subject to LDD sand impact surface

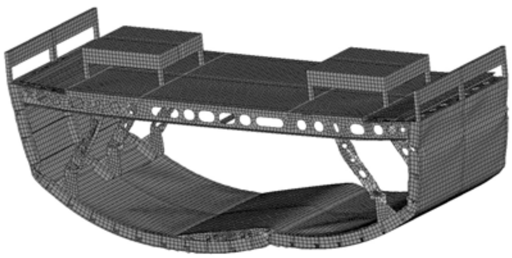

Fig. 10 Civil aircraft deformation subject to HDI sand impact surface

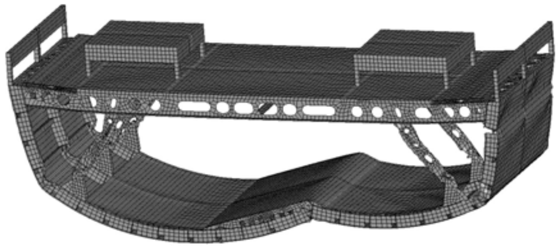

Fig. 11 Civil aircraft deformation subject to concrete impact surface

Acceleration characteristics including initial impact load and history data are the key contents for the safety of occupant. The acceleration history curves of different soft soil and concrete impact surface are exhibited as Figure 12 and 13. All the acceleration history curves have one peak, and then reduced to zero. The initial peak acceleration of soft soil ground is between 17.02g-18.94g. UWS sand is 18.94g, while other four sand materials are from 17.47g to 17.02g. They are LDD, HDI, HDF, HWS and UWS from low to high peak value. It is because that UWS sand is stiffer than other four sands. Initial peak accelerations concrete ground is between 19.70g-19.96g. It is manifest that initial peak acceleration of concrete is higher than that of soft soil.

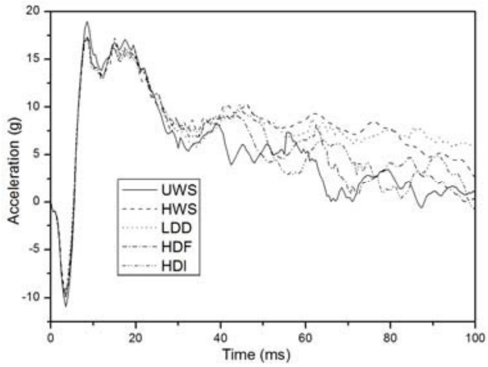

Fig. 12 Acceleration characteristics of civil aircraft with different soft soil material

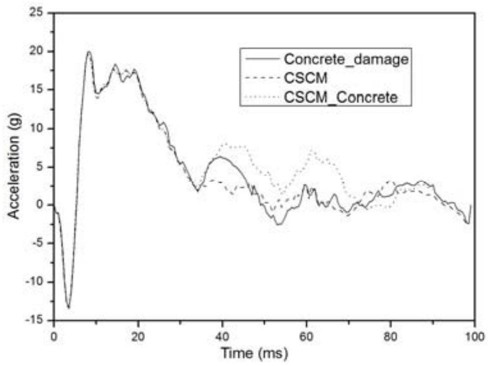

Fig. 13 Acceleration characteristics of civil aircraft with different concrete model

It could be given that the result of ground deformation, internal energy and acceleration characteristics has the same relationship. Ground with large stiffness wound have small deformation and absorb less impact kinetic energy. The corresponding civil aircraft has larger deformation and initial peak acceleration.

5. Conclusion

The crashworthiness of civil aircraft subject to soft soil and concrete impact surface is investigated here. Different soft soil and concrete materials are utilized to comprehensive study the influence of ground material. Soft soil ground could absorb a part of impact kinetic energy by deformation and function as a shock absorber. Concrete ground has larger stiffness, and dissipate little impact kinetic energy. According the buffering effect, the soft soil ground material from high to low is low density dry sand (LDD), high density in situ moisture sand (HDI), high density flooded sand (HDF), unwashed sand (UWS) and high-grade washed sand (HWS).

Acknowledgements

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